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Skin-Temperature-Responsive In Situ Hydrogel for Enhanced EMG Recording of Lumbar Muscle

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***Abstract*—Hydrogel electrodes have been widely applied in surface electromyography (EMG) signal recording due to their excellent flexibility and electrical conductivity. However, most hydrogel electrodes employ a pre-formed method, which often results in low adhesion force and poor conformity to complex skin topographies. To address the challenge, this paper proposed a skin-temperature-responsive in situ hydrogel (GPP) based on the synergistic combination of gelatin, L-Pyrrolidone Carboxylic Acid-Na (PCA-Na), and plant-derived natural polysaccharides. The GPP rapidly gels at skin temperature around 30 °C, forming a highly adhesive hydrogel with strong skin adhesion of 0.38 N/cm and a low elastic modulus of 27 kPa. As a result, a high signal-to-noise ratio (SNR) of 35.2 dB was achieved and it maintains low and stable impedance (28 kΩ) within the range of 0.1-100 Hz. As a promising in situ-forming hydrogel, GPP provides a foundation for the development of next-generation bioelectronic interfaces and offers potential applications in long-term monitoring and analysis of lumbar muscle activity.**

Keywords—electromyography, in situ hydrogel, adhesion, skin-temperature-responsive, lumbar muscle activity

I. INTRODUCTION

Hydrogels are highly hydrophilic three-dimensional polymer networks with excellent biocompatibility, stretchability, and skin-like mechanical properties [1-2]. These properties make them widely used in biomedical applications, especially in electromyography (EMG) signal recording. Although hydrogel electrodes offer excellent flexibility and conductivity, most are pre-formed, resulting in limited adhesion, poor compatibility with hairy skin, and difficulty conforming to fine skin wrinkles. This limitation restricts their potential application in EMG signal monitoring and affects signal quality. Therefore, there exists an urgent need for innovative approaches to improve the adaptability of hydrogels to complex skin surfaces, which can improve

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signal quality and enable more accurate muscle signal recording [3-5].

In recent years, modified pre-formed hydrogel electrodes have gradually become the preferred choice for EMG electrodes [6-7]. The primary reason is that the introduction of additional materials into hydrogels can enhance their conductivity, adhesion, and compatibility with the skin. In fact, researchers have successfully improved the quality of EMG signals through the method of chemically or physically modifying hydrogel electrodes [8-9]. For example, Wu's team at Jinan University developed a Janus hydrogel with asymmetric wettability. The hydrogel combines hydrophobic and hydrophilic properties. It can maintain strong adhesion on moist skin, with an adhesion force of 0.08 N/cm, which significantly improves the stability of hydrogel electrodes in sweaty environments [10]. Ye's team at Northwestern Polytechnical University proposed a starfish-inspired hydrogel electrode by incorporating tannic acid (TA) into the hydrogel. The electrode maintains a high signal-to-noise ratio (SNR) of 26.7 dB and low baseline noise of 12.8 μV even after extended use underwater, which effectively addresses the common issues of adhesion loss and signal attenuation in underwater applications [11]. Overall, these studies demonstrate that hydrogels can be modified to adapt to external environments. However, while enhancing the adhesion of hydrogels to complex skin surfaces, maintaining low and stable impedance in the range of 0.1-100Hz required for collecting EMG signals remains a key issue that needs to be addressed.

To overcome these problems, this study is aimed at developing a skin-temperature-responsive in situ hydrogel (GPP). The hydrogel is composed of gelatin, L-Pyrrolidone Carboxylic Acid-Na (PCA-Na), and plant-derived natural polysaccharides, which enables stable monitoring of lumbar signals. Due to its skin-temperature-induced in situ gelation, GPP can solidify directly on the skin, effectively filling micro-wrinkles to form a stable network and maximizing the contact area between electrodes and skin. As a result, it achieves an adhesion strength of 0.38 N/cm, a conductivity of 9.79 S/cm, a high SNR of 35.2 dB, and a low interface impedance of 28 kΩ. As a demonstration, the hydrogel is used to collect lumbar EMG signals under dynamic conditions, which showcases its potential for application on complex skin surfaces.

II. Results and Discussion

A. GPP design

To improve the adhesion of the hydrogel through skin-temperature-responsive in situ gelation and simultaneously enhance its impedance stability under low-frequency conditions, this study proposes a GPP electrode. As illustrated in Fig. 1, the preparation process of the GPP electrode involves a hydrogel solution composed of natural plant polysaccharides, gelatin, and PCA-Na. During the preparation process, natural plant polysaccharides are first mixed with deionized water and stirred at 70°C and 300 rpm for 1 hour to form the polysaccharide solution. Subsequently, gelatin is added into the solution, and the mixture is further heated and stirred at 60°C and 300 rpm for 2 hours to form a uniform solution. Next, PCA-Na is added to the polysaccharide-gelatin solution, and the mixture is stirred at 60°C and 300 rpm for 2 hours. Finally, the resulting solution is cooled to 40°C and uniformly applied to the skin electrode site. After about three minutes, a gel electrode is formed. It is worth noting that the adhesion strength of the GPP electrode reaches 0.38 N/cm, which significantly outperforms ex situ gelation hydrogels.

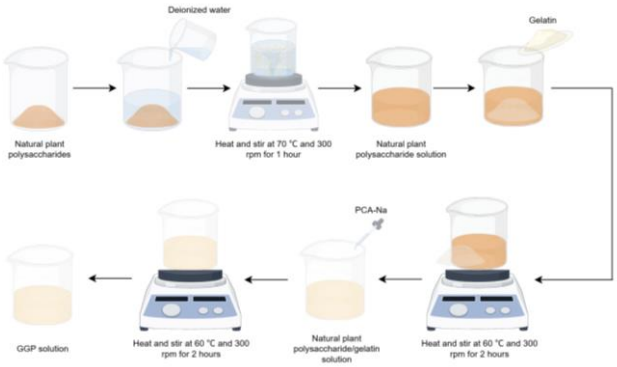
Deionized water
Gelatin
Natural plant polysaccharides
Heat and stir at 70 °C and 300 rpm for 1 hour
Natural plant polysaccharide solution
PCA-Na
GGP solution
Heat and stir at 60 °C and 300 rpm for 2 hours
Natural plant polysaccharide/gelatin solution
Heat and stir at 60 °C and 300 rpm for 2 hours

Fig. 1. The preparation process of GPP.

B. Mechanical and Rheological Properties of GPP

The mechanical and rheological properties of GPP were comprehensively characterized to evaluate its ability for stable EMG signal recording. G-P (gelatin and PCA-Na doped hydrogel) was used as the control group, and GPP X% represents the hydrogel with X% plant-derived polysaccharides, where X% denotes the percentage of plant-derived polysaccharides added. Fig. 2a shows that after adding 4% plant-derived polysaccharides, the strain of the GPP hydrogel reaches 175%, and the Young's modulus drops below 10 kPa. Compared to G-P, GPP exhibits lower stress and higher toughness under the same strain, which makes it more adaptable to various dynamic skin environments during EMG signal recording. Since plant-derived polysaccharides provide more hydrogen bonds for the hydrogel, they not only enhance the crosslinking density and flexibility but also strengthen the adhesive properties. As shown in Fig.2b, the adhesion strength of GPP reaches 0.38 N/cm, which is 80 times that of ex situ gelation hydrogels and 4 times that of G-P, which indicates that GPP exhibits greater stability in wearable bioelectronic applications. Meanwhile, the presence of numerous hydrogen bonds leads to a more compact GPP network, thereby improving the reliability of its rheological properties. Fig. 2c and 2d show that GPP transforms into a solid state at around 30°C, which is consistent with the skin surface temperature, and exhibits higher stability under low-frequency conditions in its solid state [12]. Therefore, GPP overcomes the limitations of ex situ gelation hydrogels and ensures better conformity to complex skin surfaces.

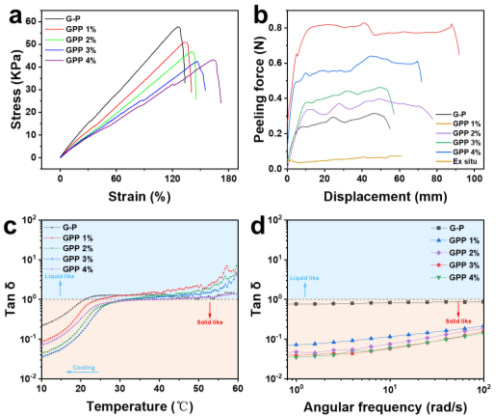

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Fig. 2. The mechanical and rheological properties of G-P and GPP. a. The stress-strain curve of G-P and GPP. b. Comparison of the peeling force of GPP and ex situ gelation hydrogels on porcine skin. c. The relationship between temperature and tanδ for GPP. d. Rheological characteristics of GPP under tensile strain frequencies of 0.1-100 Hz.

C. Conductivity properties of GPP

The mechanical properties of hydrogels determine their stability during wearing, while their conductivity is crucial for the quality of EMG signals. Therefore, this section systematically investigates the electrical properties of GPP. As shown in Fig. 3a and 3b, the conductivity of GPP is significantly higher than that of G-P, reaching 9.79 S cm^{-1}. This is because the addition of plant-derived polysaccharides enriches the hydrogen bond network of the hydrogel, leading to a denser and more efficient conductive network. Additionally, EMG signals typically lie within the low-frequency range of 0.1–100 Hz. Within this range, maintaining a stable and low impedance is essential for minimizing signal distortion and accurately detecting EMG signals. However, conventional hydrogels often exhibit a dramatic increase in impedance—up to 1500 times—as the frequency decreases from 10 Hz to 0.1 Hz [13]. In contrast, as shown in Fig. 3c, the impedance of GPP remains low and stable throughout the entire 0.1–100 Hz frequency range, demonstrating excellent ionic conductivity and strong electrode–skin coupling, which further confirms that the inclusion of plant-derived polysaccharides enhances the hydrogel's conductivity and improves its performance in signal recording.

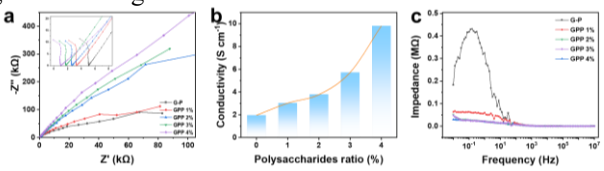

Fig. 3. Comparison of the electrical properties of G-P and GPP. a. EIS spectra of G-P and GPP. b. Comparison of the conductivity of GPP. c. The frequency response of the GPP and G-P.

D. Basic physical properties of hydrogels

Based on the above discussion, it can be found that, benefited from the incorporation of natural plant polysaccharides, both the mechanical and electrical properties of GPP are enhanced. Therefore, we conducted a series of physical characterizations to verify the formation of a stable internal network. As shown in Fig. 4a, the Fourier Transform Infrared (FTIR) spectra reveal significant differences in characteristic peaks between GPP and G-P. The –OH stretching vibration peak at 3200–3400 cm^{-1} in GPP is broader and stronger, which indicates enhanced hydrogen bonding. The C=O peak at 1600 cm^{-1} shows increased intensity, which suggests stronger interactions involving carboxyl or amide groups. Additionally, the C–O–C and C–O absorption peaks in the range of 1000–1200 cm^{-1} are more pronounced, further confirming that the incorporation of natural polysaccharides promotes the formation of a stable network, thereby improving the structural stability of GPP. The scanning electron microscopy (SEM) images further confirm the formation of the stable internal network, as shown in Fig. 4b, the surface of G-P appears relatively smooth with no obvious porous structures, while Fig.4c, the GPP sample exhibits a uniform and well-defined porous morphology. This result indicates that the incorporation of natural plant polysaccharides promotes the formation of a stable three-dimensional network within the hydrogel, which directly enhances both its electrical and mechanical properties.

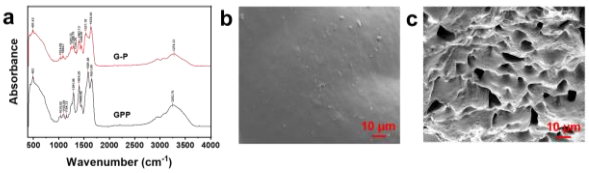

Fig. 4. Basic physical characterizations of G-P and GPP. a. FTIR spectra comparison of G-P and GPP. b, c. SEM photographs.

E. Suitability of GPP for EMG Recording at the Lumbar

After confirming the reliability of the GPP in EMG signal monitoring, it is used to monitor the lumbar muscle activity during different actions. We placed the six-channel GPP electrode patches evenly on both sides of the participant's lumbar spine to collect EMG signals from different regions on both sides of the lumbar spine, as shown in Fig. 5a. Subsequently, the participant was instructed to perform a series of movements, including body turn, stoop, and leg lift (Fig. 5b-5d). As shown in the EMG signals, different muscle groups are activated during each posture, and the corresponding channels exhibit distinct patterns. For instance, during different movements, the EMG signals from different channels exhibit distinct response patterns. CH1 and CH4 show pronounced EMG signal fluctuations during body turning, CH2 and CH5 display greater signal changes during bending, while CH3 and CH6 respond most significantly during leg lifting. This is primarily because the patch is attached to the L4-L5 spinal region, where spinal deformation is most pronounced during various activities, leading to more intense muscle activation in this area. As a result, the channels corresponding to the L4-L5 region on the back exhibit the most significant signal changes [14]. These results confirm that the GPP-based electrodes can precisely capture subtle variations in muscle activity across different lumbar regions during dynamic movements.

Due to the strong adhesion of GPP, low and stable interface impedance, the recorded signals maintained a high SNR of 35.2dB. The signal quality is much better than pre-formed hydrogels, which often suffer from motion-induced detachment and motion artifacts. With its in situ gelation, excellent mechanical and electrical properties, GPP demonstrates great potential for high-quality lumbar muscle signal recording on complex skin surfaces.

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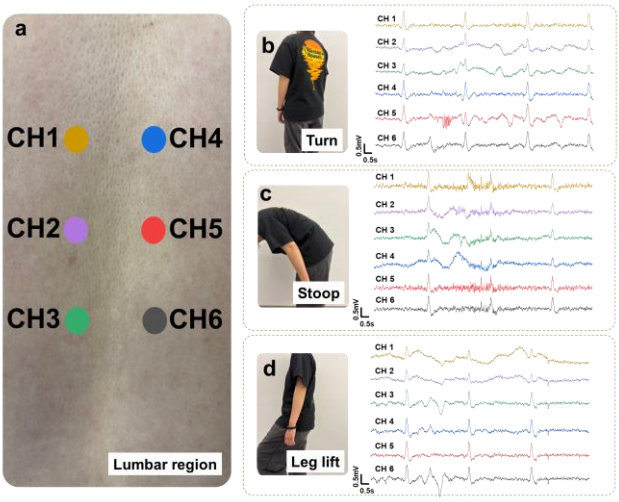

Fig. 5. Monitoring of lumbar EMG signals with different actions. a. Distribution of GPP electrode points on the lumbar region. Multichannel lumbar EMG signals under b. turn, c. stoop, and d. leg lift conditions.

III. Conclusion

This paper introduces a skin-temperature-responsive in situ gelation natural polysaccharide hydrogel, GPP, which maintains stable and low impedance at a range of 0.1-100Hz. Due to the combination of natural polysaccharides and gelatin, the hydrogel not only exhibits skin temperature-responsive properties but also maintains a stable interface impedance of around 28 kΩ in the low-frequency range of 0.1-100 Hz. Additionally, the conductivity of GPP reaches 9.79 S/cm, which allows for stable recording of high signal-to-noise ratio (SNR) EMG signals at 35.2 dB. As a result, the GPP-based electrodes successfully capture subtle variations in EMG signals across different lumbar regions during dynamic movements without motion-induced detachment and motion artifacts. The research demonstrates the great potential of GPP for long-term lumbar muscle signal monitoring on complex skin topographies.

IV. Experimental Section

Materials: Gelation powder was purchased from Aladdin and sodium pyrrolidone carboxylate (PCA-Na, AR, 50%) was purchased from Mackin. The raw material for preparing plant-derived natural polysaccharides was purchased from FZJAOZNE Co., Ltd. In addition, the pig skin was purchased from Linyi Hongqi Commercial Co., Ltd.

Rheology property test: The rheological properties of the hydrogels were characterized under a temperature ramp mode using a Discovery HR-2 rheometer (Waters Technology, USA), equipped with a 25 mm diameter parallel plate (1 mm gap) and a temperature-controlled Peltier system to ensure precise thermal regulation during measurements. The cylindrical hydrogel (25mm in diameter and 1mm in height) was applied to the Peltier plate preheated to approximately 60 °C. Subsequently, a temperature ramp test was conducted from 60 °C to 10 °C at a rate of 5 °C/min, with an oscillation frequency of 5 rad/s at a strain amplitude of 1%.

Mechanical property test: The good adhesive property of hydrogels is essential for EMG signal recording. The adhesive property of the GPP hydrogel was evaluated using a 90-degree peeling test. For the in situ gelation hydrogel test, the hydrogel precursor solution was poured directly onto the pig skin and gelled at room temperature for 10 minutes, forming a hydrogel sample with dimensions of 9 cm × 3 cm × 1 mm. For the ex situ gelation hydrogel test, a pre-formed hydrogel was placed onto the pig skin. In both cases, adhesion force was measured using a 90-degree peeling test at a constant rate of 60 mm/min, performed with a uniaxial FC038V Computer Peel Tensile Testing Machine (Guangdong Zhongyejingke Precision Scientific Instrument, China).

Electrical conductivity: Electrochemical impedance spectroscopy (EIS) was conducted using a high-performance electrochemical workstation DH7000 (Donghua, China). The measurement was conducted using a two-electrode configuration and covered a wide frequency range of 0.1Hz to 10MHz. In the electrochemical impedance spectroscopy (EIS) Nyquist plot, the resistance of the hydrogel was determined from the intercept of the curve with real axis (-Z''=0). The conductivity was then calculated using the following equation:

$$\sigma = \frac{1}{R} \times \frac{L}{S} \tag{1}$$

Where R is the resistance (Ω), L is the length of the hydrogel along the direction of current flow (1 cm), and S is the cross-sectional area perpendicular to the current flow (1 mm × 1 mm).

EMG signal monitoring: All recordings were conducted using a Sessantaquattro+ EMG system (OT Bioelettronica S.r.l., Italy). The in situ hydrogel precursor solution was carefully applied to the skin, precisely covering the designated electrode and adhesion areas. Subsequently, the electrode patch was gently pressed onto the skin to ensure close contact. The gelation process was completed within approximately 5 minutes, during which strong adhesion formed between the hydrogel and skin. After complete gelation, EMG signals were recorded using the Sessantaquattro+ system. The SNR is calculated using the following equation:

$$SNR\ (dB) = 10 \times log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \tag{2}$$

Where SNR represents the signal-to-noise ratio expressed in decibels (dB), P_{signal} represents the average power of the recorded EMG signal during muscle activation, and P_{noise} denotes the average power of the baseline noise measured during muscle rest.

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Ethics Approval

Ethics approval was obtained from all participants, and the protocol was approved by Xi'an Jiaotong-Liverppol University (ER-LRR-110000487020231102134017).

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